Mon. Not. R. Astron. Soc. **000**, 000–000 (1996)   Printed 1 February 2008   (MN plain TEX macros v1.6)

Are the X-ray spectra of flat-spectrum radio quasars and BL Lacertae objects different?

Paolo Padovani[1], Paolo Giommi[2], and Fabrizio Fiore[2,3]

[1] *Dipartimento di Fisica, II Università di Roma "Tor Vergata", Via della Ricerca Scientifica 1, I-00133 Roma, Italy*

[2] *SAX, Science Data Center, ASI, Viale Regina Margherita 202, I-00198 Roma, Italy*

[3] *Osservatorio Astronomico di Roma, Via dell'Osservatorio 5, I-00040 Monteporzio Catone (Roma), Italy*

Accepted . Received ; in original form

ABSTRACT

We study the X-ray spectra of 114 flat-spectrum radio quasars (FSRQ) using the hardness ratios as given in the WGA catalogue of *ROSAT* sources. This sample includes all WGA FSRQ with high-quality data and comprises about 20 per cent of presently known such objects, which makes this the largest FSRQ sample ever studied in the X-ray band. We find that FSRQ have a distribution of energy spectral indices ranging between 0 and 3 with a mean value $\alpha_{\rm x} \sim 1$. This is consistent with that of low-energy cutoff BL Lacs (LBL; $\alpha_{\rm x} \sim 1.1$), generally found in radio surveys, but significantly different from that of high-energy cutoff BL Lacs (HBL), normally selected in the X-ray band, which display steeper X-ray spectra ($\alpha_{\rm x} \sim 1.5$). The shape of the optical-to-X-ray continuum is concave (that is $\alpha_{\rm x} < \alpha_{\rm ox}$) for the majority of FSRQ, as found for LBL, supporting a dominance of inverse Compton emission in the X-ray band in most objects. Our results are at odds with previous studies of the X-ray spectra of FSRQ, which were however plagued by low spectral resolution and/or small number statistics and selection effects, and have important implications for the proposed connections between FSRQ and BL Lacs.

Key words: galaxies: active – BL Lacertae objects: general – Radio continuum: galaxies – quasars: general – X-rays: galaxies

1 INTRODUCTION

BL Lacertae objects constitute an extreme and relatively rare type of active galactic nuclei (AGN), characterized by high luminosity, rapid variability, high ($>$ 3 per cent) optical polarization, radio core-dominance, superluminal velocities, and almost complete lack of emission lines (e.g. Kollgaard 1994; Urry & Padovani 1995). Furthermore, the broad-band emission in these objects, which extends from the radio all the way up to the gamma-ray band, is most probably dominated by non-thermal processes, undiluted by the thermal emission present in most other AGN (e.g. Bregman 1990).

Similar properties (apart from the presence of a UV "bump" in some cases), are also displayed by a subclass of radio-loud quasars, whose spectra therefore show, by definition, strong, broad emission lines. These have typical equivalent widths much larger than 5 Å, the value below which objects are generally classified as BL Lacs (e.g. Stickel et al. 1991; Stocke et al. 1991). These quasars are defined variously as Optically Violently Variable (OVV) quasars, Highly Polarized Quasars (HPQ), Core-Dominated Quasars (CDQ), or Flat-Spectrum Radio Quasars (FSRQ), the latter indicating a radio spectral index $\alpha_{\rm r} < 0.5$ ($f_\nu \propto \nu^{-\alpha}$) at a few GHz (e.g. Urry & Padovani 1995). Although these names reflect different empirical definitions, growing evidence suggests that these various classes coincide, that is FSRQ tend to show rapid variability, high polarization, and radio structures dominated by compact radio cores, and vice versa (e.g. Fugmann 1988; Impey & Tapia 1990). BL Lacs and FSRQ are often collectively called blazars.

The relation between the two classes, if one exists, is not clear. Padovani (1992), based mostly on their different isotropic properties, has argued that BL Lacs and FSRQ represent examples of similar relativistic phenomena hosted by radio galaxies of different power, BL Lacs being associated with Fanaroff-Riley type I (i.e. low luminosity: Fanaroff & Riley 1974) radio galaxies, and FSRQ being associated with FR II (i.e. high luminosity) radio galaxies (see also Urry & Padovani 1995 and references therein). A tighter connection has also been proposed, be it through evolution (e.g. Vagnetti, Giallongo & Cavaliere 1991) or gravitational lensing (e.g. Ostriker & Vietri 1985).

An important part in the study of the relation between the two classes is played by the shape of the X-ray spectra. For example, if the majority of BL Lacs were actually gravitationally microlensed radio quasars (Ostriker and Vietri 1985), the X-ray spectra of BL Lacs and FSRQ should probably be indistinguishable (see also Worrall & Wilkes

1990). Similarly, if FSRQ evolve into BL Lacs through an increase with cosmic time of the Lorentz factor (Vagnetti et al. 1991), this should affect their X-ray spectra.

A detailed comparison of the X-ray spectra of BL Lacs and FSRQ is then clearly important in this respect, as it can further constrain the proposed connection (or lack of) between them and, more generally, shed light on the emission mechanisms responsible for the X-ray emission in both classes. Although previous results have suggested FSRQ to have harder X-ray spectra than BL Lacs, these were actually strongly affected by low spectral resolution and/or small statistics and selection biases. Worrall & Wilkes (1990) analyzed the *Einstein* IPC spectra of 31 FSRQ (including 12 HPQ) and 23 radio-selected BL Lacs (RBL). It was found that, letting $N_{\rm H}$ free to vary in the single fits, FSRQ had $\alpha_{\rm x} \sim 0.5$ while RBL had $\alpha_{\rm x} \sim 1$ (where $\alpha_{\rm x}$ denotes the energy index), which was interpreted in terms of a different mixing of beamed and unbeamed X-ray emission between the two classes. The derived spectral indices, however, had very large uncertainties due to the poor spectral resolution of the IPC experiment. More recently, Brunner et al. (1994) have studied the *ROSAT* X-ray spectra of a complete (flux limited) sample of 13 flat-spectrum sources extracted from the S5 radio catalogue, 8 FSRQ and 5 BL Lacs. They found $\alpha_{\rm x} = 0.59 \pm 0.19$ for the quasars and $\alpha_{\rm x} = 1.36 \pm 0.27$ for the BL Lacs. The two classes, however, had largely different redshift distributions, FSRQ being at higher redshift, with half the FSRQ at $z > 1.5$ and only two FSRQ in the BL Lac redshift range. The X-ray spectrum of radio-loud quasars is likely to flatten with redshift (Schartel et al. 1996; Fiore & Elvis 1995; Elvis et al. 1994; Bechtold et al. 1994), so this redshift difference is going to bias the comparison between the two classes. Finally, Urry et al. (1996) have compared the X-ray spectral index distribution of the Brunner et al. (1994) FSRQ with that of the 1-Jy sample of BL Lacs. Again, the $\alpha_{\rm x}$ distributions of the two classes are significantly different, but so are the redshift distributions, with still only two FSRQ in the BL Lac redshift range.

The purpose of this paper is to analyze the X-ray spectra of all FSRQ observed (as pointed or serendipitous sources) by *ROSAT* and compare them to those of 85 BL Lacs, studied in a previous paper (Padovani & Giommi 1996, hereafter Paper I). Our data have been taken from the WGA catalogue (White, Giommi & Angelini 1994), a large list of X-ray sources generated from all the *ROSAT* PSPC pointed observations, with which it is now possible to study the X-ray properties of large numbers of objects in an homogeneous and relatively simple way. The selection of the objects was done by cross-correlating the WGA catalogue with various optical and radio catalogues. This resulted in 225 observations of 114 FSRQ, which make up about 18 per cent of known FSRQ (see Section 2.2).

The comparison between FSRQ and BL Lac X-ray spectra can therefore be performed for the first time in a way which satisfies all of the following important requirements: large number statistics, reasonably good X-ray spectral resolution, large redshift range and in particular good overlap between the redshift distributions of the two classes (see Section 2.2). The structure of the paper is as follows: Section 2 describes the BL Lac and FSRQ samples used in this work, Section 3 deals with the observational data and their analysis, Section 4 studies the X-ray spectral properties of FSRQ while Section 5 discusses our results and presents our conclusions. Throughout this paper spectral indices are written $f_\nu \propto \nu^{-\alpha}$.

2 THE SAMPLES

2.1 BL Lacs

The BL Lac sample was put together in Paper I by cross-correlating the first revision of the *ROSAT* WGA catalogue with a recent BL Lac catalogue (Padovani & Giommi 1995b). It includes 85 sources, which correspond to ~ 50 per cent of confirmed BL Lacs presently known. BL Lacs appear to come in two types (e.g. Stocke et al. 1985; Ledden & O'Dell 1985; Giommi, Ansari & Micol 1995; Padovani & Giommi 1995a): those with a peak in their broad-band spectrum at relatively low (infrared/optical) energies (LBL), mostly found in radio surveys, and those with a peak at relatively high (ultraviolet/X-ray) frequencies (HBL), which are typically selected in the X-ray band. The dividing line between the two classes is at a ratio $f_{\rm x}/f_{\rm r} \sim 10^{-11.5}$ (with X-ray fluxes in the 0.3 – 3.5 keV range in units of erg cm^{-2} s^{-1} and radio fluxes at 5 GHz in janskys), HBL having an X-ray-to-radio flux ratio above this value (Paper I). The properties of the two subclasses are somewhat different, those of LBL being more extreme (Kollgaard 1994; Urry & Padovani 1995). Giommi et al. (1995) and Padovani & Giommi (1995a) have argued that there may be only one population of objects, characterized by a wide range of peak energies, and that the existence of two classes simply reflects the different selection criteria of radio and X-ray surveys. Our BL Lac sample includes 58 HBL and 27 LBL (see Paper I).

2.2 Flat-spectrum radio quasars

The FSRQ were selected by cross-correlating the first revision of the WGA catalogue (restricting ourselves to sources with quality flag ≥ 5, which excludes problematic detections) with a variety of optical and radio catalogues, including the Véron-Cetty & Véron (1993) and Hewitt & Burbidge (1993) quasar catalogues, and the 1-Jy (Stickel, Meisenheimer & Kühr 1994) and S4 (Stickel & Kühr 1994) radio catalogues. All objects in this study are "bona fide" quasars, that is objects whose optical spectrum has a strong nonstellar component and shows broad lines. Broad-line radio galaxies (with flat radio spectra) are then also included (see e.g. Urry & Padovani 1995). Two sources classified as quasars in the Parkes catalogue on the basis of their optical "stellar" appearance and for which no redshift was available were excluded. 3C 111, known to be strongly absorbed (Nandra & Pounds 1994), and NRAO 140, for which there is evidence of variable absorption (Turner et al. 1995), were also excluded. Excluding from our analysis observations with values of hardness ratios relative to their uncertainties < 3.5 (see Section 3), we are then left with 225 observations of 114 FSRQ, which make up about 18 per cent of the FSRQ listed in the Véron-Cetty & Véron (1993) catalogue. This represents the largest number of FSRQ for which homogeneous X-ray spectral information is available and the largest FSRQ sample ever studied at X-ray frequencies. The flat radio spectrum classification ($\alpha_{\rm r} < 0.5$) refers to the spectrum

at a few GHz and has been made on the basis of radio data provided by a variety of radio catalogues. Fifty-eight objects, that is about 50 per cent of the sample, belong to the 1-Jy radio catalogue (Stickel et al. 1994), an all-sky flux-limited sample which includes 527 sources with 5 GHz fluxes ≥ 1 Jy, 222 of which are FSRQ. Twenty-four objects, that is about 20 per cent of the sample, belong to the 2-Jy radio catalogue (Wall & Peacock 1985), an all-sky flux-limited sample which includes 233 sources with 2.7 GHz fluxes ≥ 2 Jy, 51 of which are FSRQ.

Fig. 1 shows the redshift distribution of the FSRQ sample, which extends up to $z \sim 4$ with $\langle z \rangle = 1.33 \pm 0.08$ (here and in the following we give the standard deviation of the mean). The figure shows also the redshift distributions of the LBL and HBL objects with redshift information (~ 80 per cent of the BL Lac sample): the overlap between FSRQ and LBL is substantial, with 50 FSRQ (44 per cent of the sample) having $z \leq 1.048$, the maximum BL Lac redshift. The detailed redshift dependence of the X-ray spectral indices of FSRQ will be studied elsewhere (Fiore et al., in preparation) but we can anticipate that a correlation between $\alpha_{\rm x}$ and redshift seems to be present only when objects with $z \gtrsim 2$ are included. In the following, then, we will compare the X-ray properties of BL Lacs to those of the whole FSRQ sample and, to exclude the likely redshift dependence, to those of the $z \leq 2$ subsample (90 sources, 79 per cent of the sample) and the $z \leq 1.048$ subsample (50 sources, 44 per cent of the sample). While the former subsample represents a compromise between good number statistics and a relatively low mean redshift, the latter has a redshift distribution indistinguishable from that of the LBL sample according to a Kolmogorov-Smirnov (KS) test.

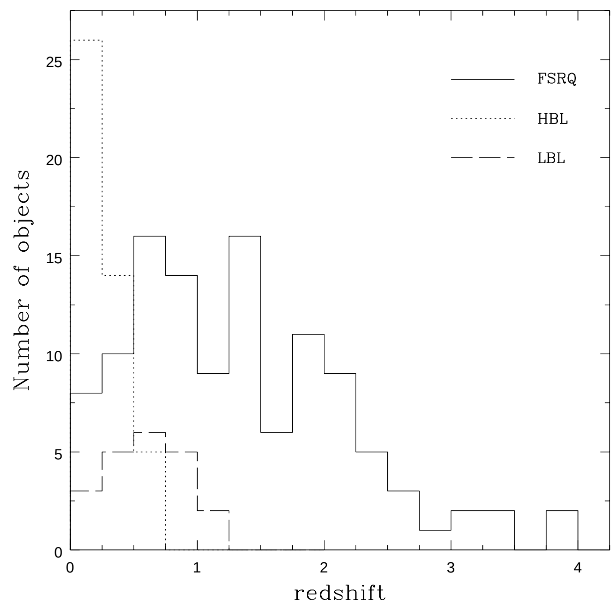

Figure 1. The redshift distribution of the FSRQ sample (solid line), compared to that of the HBL (BL Lacs with $f_{\rm x}/f_{\rm r} \geq 10^{-11.5}$: dotted line) and the LBL (BL Lacs with $f_{\rm x}/f_{\rm r} < 10^{-11.5}$: dashed line) studied in Paper I. BL Lacs without redshift information are not included.

3 DATA ANALYSIS

Spectral indices for the WGA FSRQ were obtained as described in Paper I for the BL Lacs. Namely, we derived hardness (HR) and softness (SR) ratios from the count rates given in the catalogue in the $0.1-0.4$ keV range (soft band: S), $0.4-0.86$ keV range (mid band: M) and $0.87-2.0$ keV range (hard band: H). The count rates were then combined to construct one $SR = S/M$ and two HRs, $HR_1 = H/M$ and $HR_2 = H/(M+S)$. Initially we converted the hardness ratios into energy spectral indices both assuming Galactic $N_{\rm H}$ derived from 21 cm measurements (Stark et al. 1992; Shafer et al., private communication) and with $N_{\rm H}$ derived from the softness ratio through an iterative procedure. The spectral indices derived from the two approaches were found to be similar and well correlated in the $0.4-2.0$ keV range, while considerable scatter was present when the total *ROSAT* band was considered, with a few objects having $\alpha_{\rm x,NH}$ significantly different from $\alpha_{\rm x,Galactic\ NH}$, suggestive of a change of the spectrum at lower energies. In this paper, as in Paper I, we will adopt as X-ray spectral index the value obtained with $N_{\rm H}$ fixed to the Galactic value, which is better determined than the $N_{\rm H}$ derived from the softness ratios, and in the $0.4-2.0$ keV range, i.e. the mid to hard band.

The choice of this energy range stems from two facts: first, our method *assumes* a single power-law; some objects, however, show evidence of low-energy absorption (Fiore et al., in preparation), so this assumption might be incorrect in the whole *ROSAT* range while it is probably more acceptable in the narrower $0.4-2.0$ keV range (as shown by the similarity of the spectral indices obtained with Galactic $N_{\rm H}$ and $N_{\rm H}$ derived from the softness ratio); second, the method used in the WGA catalogue to estimate the source intensity uses the counts detected in a box whose size optimises the signal to noise (S/N) ratio. This size is calculated assuming an average point spread function (PSF) that is too sharp for very soft photons. For weak sources near the field center the adopted box size is small and includes an energy-dependent fraction of the source photons causing an underestimation of the counts in the soft band. The effects of the dependence of energy response with off-axis angle have been taken into account using different conversion matrices in five different off-axis ranges: $0-20$, $20-30$, $30-40$, $40-50$, and $50-60$ arcminutes. Note that this method of estimating spectral indices is quite robust, as shown in Paper I, and particularly suitable for the determination of the X-ray spectral slope distribution for large samples of objects (Giommi et al., in preparation).

Errors on the spectral indices (1σ) were derived from the uncertainties on the hardness ratios. We included in our analysis only observations with values of hardness ratios relative to their uncertainties > 3.5, which corresponds roughly to 1σ errors on $\alpha_{\rm x} \lesssim 0.5$ (Giommi et al., in preparation).

A few FSRQ have been repeatedly observed, typically in the course of multi-frequency campaigns (e.g. 3C 273, 3C 279) and in general many sources have more than one observation. Inclusion of all these data in statistical studies (means, correlations, KS tests etc.) would clearly bias them, as the results would be weighed towards the sources with the largest number of observations. Therefore, although we plot in some figures the data referring to all 225 observations, in

the statistical tests we have kept only one observation (and therefore one spectral index) per object, selected on a one-to-one basis taking the best combination of offset from the field center and S/N ratio. When more than two observations with comparable offset and S/N ratios were available, we selected as most representative the one with α_x closest to the mean value for that source.

4 THE X-RAY SPECTRA

The X-ray spectral index distribution of the FSRQ in our sample is shown in Fig. 2. The mean value is $\langle\alpha_{x,\mathrm{FSRQ}}\rangle = 1.04 \pm 0.05$ (see also Table 1). A KS test shows that this distribution and that of the 85 BL Lacs studied in Paper I ($\langle\alpha_x\rangle = 1.37 \pm 0.05$) are different at the 99.99 per cent level. Even if one compares the BL Lacs to the $z \le 2$ and $z \le 1.048$ FSRQ subsamples (which have slightly steeper averages $\langle\alpha_x\rangle = 1.09\pm0.05$ and $\langle\alpha_x\rangle = 1.16\pm0.06$: see Table 1), the BL Lac and FSRQ α_x distributions are still different at the 99.8 and 97.1 per cent level respectively. However, this is clearly due to the relative steepness of the X-ray spectra of HBL ($\langle\alpha_{x,\mathrm{HBL}}\rangle = 1.52 \pm 0.06$). In fact, the α_x distribution of the 27 LBL, for which $\langle\alpha_{x,\mathrm{LBL}}\rangle = 1.06 \pm 0.09$, is *fully consistent* with that of the whole FSRQ sample (see Fig. 2) and the two lower redshift subsamples, according to a KS test.

Paper I showed that the X-ray spectral slope of HBLs was strongly correlated with the effective optical-X-ray spectral index α_{ox} (evaluated between the rest-frame frequencies of 5000 Å and 1 keV), indicative of a common origin for the optical/X-ray emission in those objects. Moreover, all but one HBL had an overall convex spectrum, that is $\alpha_x \ge \alpha_{ox}$ (within the errors). On the other hand, no such correlation was present for LBL, the majority of which had $\alpha_x < \alpha_{ox}$, that is a concave optical-X-ray spectrum. It is therefore interesting to see how FSRQ behave in this respect. Fig. 3 plots α_x versus α_{ox} for FSRQ and LBL (the latter data from Paper I; HBL are not included to improve legibility). Optical fluxes for FSRQ were derived from the V magnitudes included in the catalogues listed in Section 2.2, correcting for Galactic absorption following Giommi et al. (1995), while 1 keV fluxes have been obtained from the *ROSAT* counts and the derived spectral indices and have also been corrected for Galactic absorption. The k-correction has been derived assuming an optical index $\alpha_o = 1$, a value which is intermediate between $\alpha_o = 1.4$, reported by Ghisellini et al. (1986) for 6 blazars with strong emission lines, and $\alpha_o = 0.5$, obtained by Baker & Hunstead (1995) for 13 core-dominated quasars. Note that optical fluxes are not simultaneous with X-ray data which, given the strong optical/X-ray variability of FSRQ, will certainly introduce a scatter: a variation ΔV in magnitude, for example, translates into a change $\Delta\alpha_{ox} = 0.15\Delta V$.

The data presented in Fig. 3 show that, as is the case for LBL, there is no correlation between α_x and α_{ox} for FSRQ. Moreover, the distribution of the two classes on the α_x - α_{ox} plane is indistinguishable according to a two-dimensional KS test (Fasano & Franceschini 1987). It then follows that the $\alpha_x - \alpha_{ox}$ distributions of the two classes cannot be that different, as illustrated by Fig. 4. In fact, $\langle\alpha_x - \alpha_{ox}\rangle = -0.33\pm0.09$ for LBL (Paper I) and -0.28 ± 0.05 for FSRQ, with the latter value changing to -0.22 ± 0.05 for $z \le 2$ and to -0.12 ± 0.06 for $z \le 1.048$ (Table 1). According to a Student's t-test, the mean values for BL Lacs and FSRQ are not significantly different in all cases, although barely so for the $z \le 1.048$ FSRQ subsample (which has a value of $\langle\alpha_x - \alpha_{ox}\rangle$ different from that of LBL at the 94 per cent level). For comparison, Fig. 4 shows also the $\alpha_x - \alpha_{ox}$ distribution for HBL, from Paper I, clearly different from that of both FSRQ and LBL, with $\langle\alpha_x - \alpha_{ox}\rangle = 0.40\pm0.04$. This reflects the different distributions of HBL on the α_x - α_{ox} plane (see Paper I). Note also that only 30 per cent of FSRQ have convex optical-to-X-ray continua (i.e. $\alpha_x > \alpha_{ox}$), to be compared with 25 per cent of LBL (and 98 per cent of HBL; see Paper I). Assuming that the errors associated with $\alpha_x - \alpha_{ox}$ equal those on α_x, a clearly conservative assumption, it turns out that only 13 FSRQ (or 11 per cent of the sample) have $\alpha_x > \alpha_{ox}$ at the $\gtrsim 2\sigma$ level. This is similar to the fraction of LBL (15 per cent; Paper I) having convex spectra at the same significance level.

Table 1. Mean values.

Sample	N	$\langle\alpha_x\rangle$	$\langle\alpha_x - \alpha_{ox}\rangle$	Notes
FSRQ	114	1.04 ± 0.05	-0.28 ± 0.05	This work
FSRQ ($z \le 2$)	90	1.09 ± 0.05	-0.22 ± 0.05	This work
FSRQ ($z \le 1.048$)	50	1.16 ± 0.06	-0.12 ± 0.06	This work
All BL Lacs	85	1.37 ± 0.05	0.17 ± 0.06	Paper I
LBL	27	1.06 ± 0.09	-0.33 ± 0.09	Paper I
HBL	58	1.52 ± 0.06	0.40 ± 0.04	Paper I

Mean α_x and $\alpha_x - \alpha_{ox}$ values for the samples discussed in this paper. N is the number of objects in the various samples.

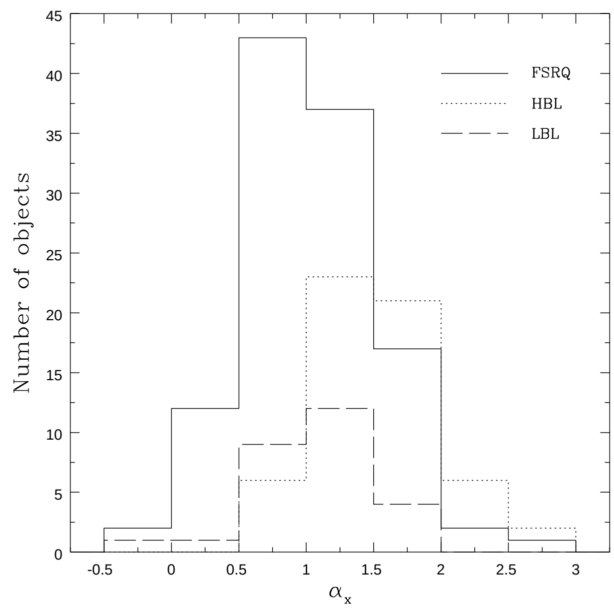

Figure 2. The X-ray spectral index distribution of the FSRQ in our sample (solid line), compared to that of the HBL (BL Lacs with $f_x/f_r \ge 10^{-11.5}$: dotted line) and the LBL (BL Lacs with $f_x/f_r < 10^{-11.5}$: dashed line) studied in Paper I. Only one X-ray spectrum per object is used, as described in Section 2. The distributions of FSRQ and LBL are indistinguishable according to a KS test.

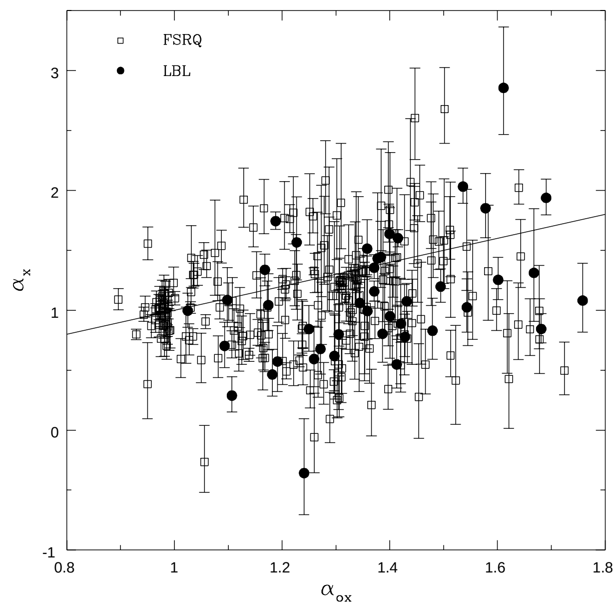

Figure 3. The X-ray spectral index versus $\alpha_{\rm ox}$ for the FSRQ in our sample and the LBL studied in Paper I. Filled points indicate LBL (BL Lacs with $f_{\rm x}/f_{\rm r} < 10^{-11.5}$), while open squares indicate FSRQ. The solid line represents the locus of points having $\alpha_{\rm x} = \alpha_{\rm ox}$. Error bars represent 1σ errors.

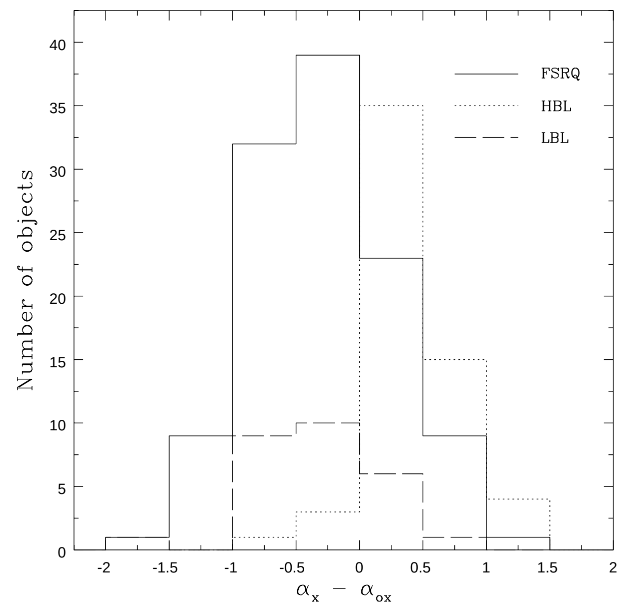

Figure 4. The distribution of $\alpha_{\rm x}$ minus $\alpha_{\rm ox}$ for the FSRQ in our sample (solid line), compared to that of the HBL (BL Lacs with $f_{\rm x}/f_{\rm r} \geq 10^{-11.5}$: dotted line) and the LBL (BL Lacs with $f_{\rm x}/f_{\rm r} < 10^{-11.5}$: dashed line) studied in Paper I. Only one X-ray spectrum per object is used, as described in Section 2. The distributions of FSRQ and LBL are indistinguishable according to a KS test.

5 DISCUSSION AND CONCLUSIONS

The data presented in this paper indicate that the X-ray spectra of FSRQ are similar to those of LBL. Moreover, the two classes have also a similar distribution on the $\alpha_{\rm x}$ - $\alpha_{\rm ox}$ plane and similar mean values of $\alpha_{\rm x} - \alpha_{\rm ox}$, with most sources exhibiting a concave optical/X-ray continuum. On the other hand, the X-ray spectra of FSRQ are, on average, flatter than those of HBL, which moreover display an overall convex spectrum.

Paper I showed that the X-ray spectra of the two BL Lac classes were different, HBL having steeper spectra. This and other results tied in with the different multifrequency spectra and suggested that while the flatter X-ray emission of LBL was dominated by inverse Compton emission, as the synchrotron break in these objects is in the infrared/optical band, that of HBL was an extension of the synchrotron emission also responsible for the lower energy continuum.

The results of the present paper, therefore, favour a dominance of inverse Compton emission in FSRQ as well. (This does not necessarily mean that the *ROSAT* band is dominated by pure Compton emission in *all* FSRQ, as some objects do display a steep spectrum, most probably due to some other soft component. One would expect, however, that FSRQ as a class had a flatter spectral slope at harder X-ray energies such as those accessible to *SAX* and *ASCA*.) As a corollary, then, one would infer that most FSRQ should have the peak of their emission at infrared/optical frequencies and therefore their broad-band spectra should be quite similar to those of LBL. (A complication here is represented by the possible presence of a UV "bump" in FSRQ, i.e. of an optical thermal component independent of the non-thermal processes present in BL Lacs, which would also increase $\alpha_{\rm ox}$ for FSRQ. Given the relatively steep UV spectral indices of CDQ [i.e. FSRQ; Wills et al. 1995], however, its contribution is probably minor, although possibly not negligible, in most objects. Notable exceptions, however, exist and include, for example, 3C 273).

It has been known for some time that radio-loud quasars and radio-selected BL Lacs occupy similar regions of the $\alpha_{\rm ro}$ - $\alpha_{\rm ox}$ plane, where the effective spectral indices are defined in the usual way and calculated here between the rest-frame frequencies of 5 GHz, 5000 Å and 1 keV (e.g. Stocke et al. 1985; Stocke et al. 1991; Padovani 1992). Fig. 5 shows that to be the case also when only FSRQ are considered: the distribution on the $\alpha_{\rm ro}$ - $\alpha_{\rm ox}$ plane for the objects studied in this paper is largely overlapping with that of LBL and clearly distinct from that of HBL. Although some FSRQ "invade" the HBL region they do so only marginally. The question of why we do not see a population of FSRQ with broad-band continua peaked in the X-ray band and therefore similar to those of HBL is an intriguing open problem which we hope to address in a future paper.

The results of our study disagree with those obtained in previous papers, which found a difference between the X-ray spectra of FSRQ and BL Lacs. Worrall & Wilkes (1990), using the *Einstein* IPC, derived $\alpha_{\rm x} \sim 0.5$ for 31 FSRQ and $\alpha_{\rm x} \sim 1$ for 23 radio-selected BL Lacs. Given that only six of their FSRQ have $z > 2$, it is unlikely that this difference is due to the flattening of $\alpha_{\rm x}$ with redshift, previously discussed. Also, their spectral slopes were affected by very large errors due to the poor spectral resolution of the IPC experiment (the majority of the sources had 90 per cent upper error bars larger than 1, with many objects having 90

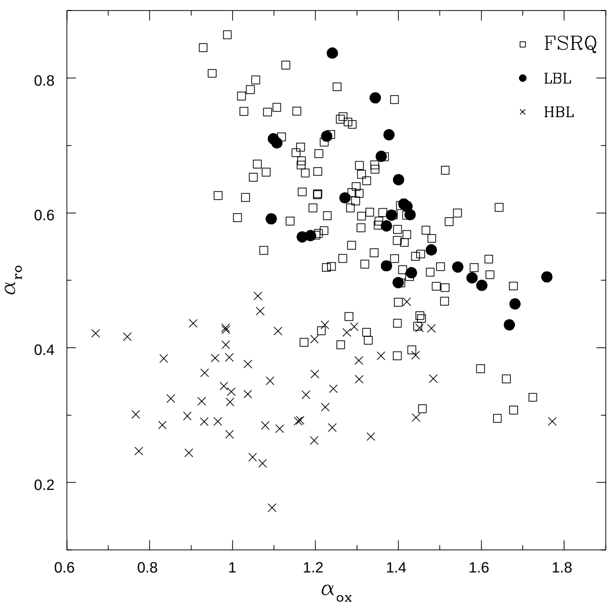

Figure 5. $\alpha_{\rm ro}$ - $\alpha_{\rm ox}$ plane for the FSRQ and BL Lacs studied in this paper and in Paper I. The effective spectral indices are defined in the usual way and calculated between the rest-frame frequencies of 5 GHz, 5000 Å and 1 keV. Crosses indicate HBL (BL Lacs with $f_{\rm x}/f_{\rm r} \geq 10^{-11.5}$), filled circles indicate LBL (BL Lacs with $f_{\rm x}/f_{\rm r} < 10^{-11.5}$), while open squares represent FSRQ. To improve legibility, only one point per object, selected as described in Section 2, is plotted. Note that FSRQ and LBL occupy roughly the same region, distinct from that typical of HBL.

per cent upper error bars in excess of 2) but it is hard to see how this could affect differently the derived spectral slopes for the two classes. A possible explanation for this difference could be the following: 1. as described in Section 3, our spectral indices have been derived assuming Galactic $N_{\rm H}$, based on the similarity between spectral slopes derived under this assumption and those obtained with $N_{\rm H}$ being a free parameter. In the case of Galactic absorption, Worrall & Wilkes (1990) obtained $\alpha_{\rm x} \approx 0.5 - 0.6$ *both* for FSRQ and RBL (see their Fig. 5). Their Table 4 shows that the assumption $N_{\rm H} = N_{\rm H,gal}$, once the few objects for which this gives poor fits (4 RBL and 4 FSRQ) are excluded, is acceptable statistically for all classes. Note also that Urry et al. (1996), in their detailed spectral analysis of *ROSAT* data for 28 1-Jy RBL, have found that most objects are well fitted by a single power-law model with Galactic absorption; 2. it is well known that there is a systematic difference between the IPC and PSPC spectral indices of about $0.4 - 0.5$, the former being harder (Fiore et al. 1994; Urry et al. 1996; Ciliegi & Maccacaro 1996). This has been interpreted in terms of two possible effects: 1. systematic errors in the calibration of both instruments (Fiore et al. 1994); 2. a concave X-ray spectrum, as the IPC band has a higher mean effective energy (Urry et al. 1996). These effects might explain the different energy indices obtained by us and by Worrall & Wilkes (1990) for FSRQ and RBL, under the same assumption of Galactic absorption.

As regards the Brunner et al. (1994) *ROSAT* results, who found $\alpha_{\rm x} = 0.59 \pm 0.19$ and $\alpha_{\rm x} = 1.36 \pm 0.27$ for 8 S5 FSRQ and 5 S5 BL Lacs respectively, there the problem stems, oddly enough, from their use of a "complete" (flux-limited) sample. It is well known that FSRQ are more luminous than BL Lacs (see e.g. Padovani 1992). Therefore, in flux-limited samples FSRQ are bound to reach higher redshifts. For example, in the 2-Jy catalogue (Wall & Peacock 1985; di Serego Alighieri et al. 1994) $\langle z_{\rm BLLacs}\rangle \simeq 0.3$ while $\langle z_{\rm FSRQ}\rangle \simeq 1.1$. Similarly, in the 1-Jy catalogue (Stickel et al. 1994), $\langle z_{\rm BLLacs}\rangle \simeq 0.5$ while $\langle z_{\rm FSRQ}\rangle \simeq 1.2$. The S5 sample is no exception, so the two classes have largely different and barely overlapping redshift distributions. In fact, $\langle z_{\rm BLLacs}\rangle \simeq 0.4$ while $\langle z_{\rm FSRQ}\rangle \simeq 1.5$, with only two out of eight FSRQ having $z \leq 0.77$, the largest redshift for the BL Lacs (and these low-redshift FSRQ have $\alpha_{\rm x} \sim 1$), while four FSRQ (i.e. 50 per cent) are at $z > 1.5$ (three at $z > 2$). Dividing the FSRQ sample of Brunner et al. in two subsamples we find that the four FSRQ with $z > 1.5$ have $\alpha_{\rm x} = 0.05 \pm 0.22$, while the four FSRQ at lower redshift have $\alpha_{\rm x} = 0.91 \pm 0.17$ (the latter different from the former at the $\sim 3\sigma$ level). Given this flattening with redshift of the X-ray energy indices of FSRQ (particularly marked at $z > 2$: Fiore et al., in preparation), it is not surprising that Brunner et al. find that the FSRQ in their sample have flatter spectra than their BL Lacs (which moreover include an HBL). Our larger and non flux-limited sample allows us to better cover the parameter space, particularly the $\alpha_{\rm x}$ - z plane, with a resulting large overlap between the redshift distributions of FSRQ and BL Lacs.

Sambruna, Maraschi & Urry (1996) have recently studied the multifrequency spectra of the 1-Jy RBL, the *Einstein* Extended Medium Sensitivity Survey (EMSS) X-ray selected BL Lacs (XBL), and the S5 FSRQ of Brunner et al. (1994). Their results on the shape of the optical-to-X-ray-continua of HBL ($\simeq$ XBL) and LBL ($\simeq$ RBL) agree with those of Padovani & Giommi (1996). However, they find that FSRQ have concave only (that is $\alpha_{\rm x} < \alpha_{\rm ox}$ for all objects) spectra, at variance with the $\alpha_{\rm x} - \alpha_{\rm ox}$ distribution derived in this paper, which shows that, although the majority of FSRQ have indeed concave optical-to-X-ray- continua, a few objects with convex spectra exist, as is the case for LBL (compare our mean value for FSRQ $\langle \alpha_{\rm x} - \alpha_{\rm ox} = -0.28\rangle$, which gets even higher at lower redshifts, with their value $\langle \alpha_{\rm x} - \alpha_{\rm ox}\rangle = -1.01$, and our Fig. 4 with their Fig. 2, taking into account that they use the parameter $\alpha_{\rm ox} - \alpha_{\rm x}$). Again, this is due to the bias towards flat X-ray spectra intrinsic in the Brunner et al. sample, discussed above. Based on these results, Sambruna et al. (1996) have introduced a subclass of RBL, named FSRQ-like, defined by $\alpha_{\rm x} - \alpha_{\rm ox} < -0.5$, to characterize RBL with extremely concave X-ray spectra. As we have shown that the $\alpha_{\rm x} - \alpha_{\rm ox}$ mean values for LBL and FSRQ are quite similar and that in fact the majority of FSRQ has $\alpha_{\rm x} - \alpha_{\rm ox} > -0.5$, we believe there is no need to introduce this new class of RBL.

What are the implications of our findings for the proposed connections between FSRQ and BL Lacs? The fact that the X-ray spectra of FSRQ and LBL are similar might seem to be a point in favour of the microlensing hypothesis (Ostriker & Vietri 1985). In this picture, microlensing by stars in a foreground galaxy could turn a distant FSRQ into a BL Lac by amplification of the relatively compact optical continuum and consequent reduction of the equivalent widths of the emission lines. Given that models of contin-

uum emission in blazars suggest relatively small sizes for the X-ray sources (e.g. Ghisellini & Maraschi 1989), and that gravitational lensing is an achromatic process, one would then expect the X-ray spectra of FSRQ and BL Lacs to be indistinguishable. However, the question then rises: what about HBL? Why should there be a population of BL Lacs with X-ray spectra steeper than both FSRQ and LBL? One would then be forced to argue that the two classes of BL Lacs represent indeed completely different phenomena, LBL being microlensed FSRQ and HBL being "true" BL Lacs. Having two different mechanisms which produce two classes with quite similar properties would clearly be an unappealing situation requiring some sort of "cosmic conspiracy". A possible way out would be to say that, as HBL have multifrequency spectra different from those of FSRQ, they could be the micro-lensed version of some other class of sources, which should have similar properties to those of FSRQ without having the same multifrequency spectra. The existence of such a class of objects is still an open question. It is our view, however, given also the various problems of the microlensing hypothesis as an explanation of the BL Lac phenomenon (Urry & Padovani 1995), that the fact that only one class of BL Lacs has X-ray spectra similar to those of FSRQ may actually be yet one more argument against it.

If FSRQ evolve into BL Lacs through an increase with cosmic time of the Lorentz factor (Vagnetti et al. 1991; Vagnetti & Spera 1994), this should affect their X-ray spectra. The shape of the X-ray emission depends in some jet models on the Doppler factor of the emitting material, as the bulk velocity increases along the jet (e.g. Ghisellini & Maraschi 1989). The net result is that in less beamed objects synchrotron emission should dominate the X-ray band, while the flatter inverse Compton radiation should be more important in sources with higher Doppler factor. It then follows that, in this picture, BL Lacs should have flatter X-ray spectra than FSRQ, in contrast with our results, which would suggest, at a first order, similar Doppler factors for the two classes. It should be kept in mind, however, that this is a model-dependent conclusion and that other parameters, beside orientation (e.g., magnetic field, jet size, etc.) affect the shape of the emission (see e.g. Sambruna et al. 1996).

The main conclusions of this paper, which studies the *ROSAT* X-ray spectra of more than one hundred FSRQ, can be summarized as below.

FSRQ are characterized by energy power-law spectral indices ranging between ~ 0 and 3, with an average value ~ 1. No correlation is present between $\alpha_{\rm x}$ and the effective optical-X-ray spectral index, with the majority of sources (70 per cent) displaying a concave overall spectrum (i.e. $\alpha_{\rm x} < \alpha_{\rm ox}$). This is similar to what found for LBL (BL Lacs with low frequency – infrared/optical – breaks in their spectra) in Paper I. Moreover, contrary to the results obtained in previous studies, which were however strongly affected by low spectral resolution, small number statistics and selection biases, the X-ray spectral indices distributions of FSRQ and LBL are indistinguishable, while both classes have X-ray spectra that are significantly flatter than those of HBL (BL Lacs with high frequency – UV/X-ray – breaks in their spectra).

These findings strongly support the hypothesis that in most FSRQ, as in LBL, an inverse Compton component dominates the X-ray emission, and favour the idea that FSRQ and BL Lacs represent similar phenomena, hosted by radio galaxies of different power.

ACKNOWLEDGMENTS

We thank Fausto Vagnetti for useful discussions. This research has made use of the BROWSE program developed by the ESA/EXOSAT Observatory and by NASA/HEASARC and of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautic and Space Administration.

REFERENCES

Baker J. C., Hunstead R. W., 1995, ApJ, 452, L95
Bechtold J. et al., 1994, AJ, 108, 759
Bregman J. N., 1990, A&AR, 2, 125
Brunner H., Lamer G., Worrall D. M., Staubert R., 1994, A&A, 287, 436
Ciliegi P., Maccacaro T., 1996, MNRAS, in press
di Serego Alighieri S., Danziger J., Morganti R., Tadhunter C., 1994, MNRAS, 269, 998
Elvis M., Fiore F., Wilkes B. J., McDowell J. C., Bechtold J., 1994, ApJ, 422, 60
Fanaroff B. L., Riley J. M., 1974, MNRAS, 167, L31
Fasano G., Franceschini F., 1987, MNRAS, 225, 155
Fiore F., Elvis M., 1995, Proceedings of the 30th COSPAR meeting, in press
Fiore F., Elvis M., McDowell J. C., Siemiginowska A., Wilkes B. J., 1994, ApJ, 431, 515
Fugmann W., 1988, A&A, 205, 86
Ghisellini G., Maraschi L., Tanzi E. G., Treves A., 1986, ApJ, 310, 317
Ghisellini G., Maraschi L., 1989, ApJ, 340, 181
Giommi P., Ansari S. G., Micol A., 1995, A&AS, 109, 267
Hewitt A., Burbidge G., 1993, ApJS, 87, 451
Impey C. D., Tapia S., 1990, ApJ, 354, 124
Nandra K., Pounds K. A., 1994, MNRAS, 268, 405
Kollgaard R. I., 1994, Vistas Astron., 38, 29
Ledden J. E., O'Dell S. L., 1985, ApJ, 298, 630
Ostriker J. P., Vietri M., 1985, Nature, 318, 446
Padovani P., 1992, MNRAS, 257, 404
Padovani P., Giommi P., 1995a, ApJ, 444, 567
Padovani P., Giommi P., 1995b, MNRAS, 277, 1477
Padovani P., Giommi P., 1996, MNRAS, 279, 526 (Paper I)
Sambruna R. M., Maraschi L., Urry C. M., 1996, ApJ, 463, 444
Schartel N., Walter R., Fink H. H., Trümper J., 1996, A&A, 307, 33
Stark A. A., Gammie C. F., Wilson R. W., Bally J., Linke R. A., Heiles C., Hurwitz M., 1992, ApJS, 77
Stickel M., Kühr H., 1994, A&AS, 103, 349
Stickel M., Meisenheimer K., Kühr H., 1994, A&AS, 105, 211
Stickel M., Padovani P., Urry C. M., Fried J. W., Kühr H., 1991, ApJ, 374, 431
Stocke J. T., Liebert J., Schmidt G., Gioia I. M., Maccacaro T., Schild R. E., Maccagni D., Arp H. C., 1985, ApJ, 298, 619
Stocke J. T., Morris S. L., Gioia I. M., Maccacaro T., Schild R., Wolter A., Fleming T. A., Henry J. P., 1991, ApJS, 76, 813
Turner T. J., George I. M., Madejski G. M., Kitamoto S., Suzuki T., 1995, ApJ, 445, 660
Urry C. M., Padovani P., 1995, PASP, 107, 803
Urry C. M., Sambruna R. M., Worrall D. M., Kollgaard R. I., Feigelson E., Perlman, E. S., Stocke J. T., 1996, ApJ, 463, 424
Vagnetti F., Giallongo E., Cavaliere A., 1991, ApJ, 368, 366

Vagnetti F., Spera R., 1994, ApJ, 436, 611
Véron-Cetty M.-P., Véron P., 1993, A Catalogue of Quasars and Active Nuclei, 6th ed. ESO Scientific Report No. 13
Wall J. V., Peacock J. A., 1985, MNRAS, 216, 173
White N. E., Giommi P., Angelini L., 1994, IAU circ. 6100
Wills B. J. et al., 1995, ApJ, 447, 139
Worrall D. M., Wilkes B. J., 1990, ApJ, 360, 396